Rigid body motions capturing by means of wearable inertial and magnetic MEMS sensors assembly : from the reconstitution of the posture toward the dead reckoning: an application in Bio-logging

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Rigid body motions capturing by means of wearable inertial and magnetic MEMS sensors assembly: toward the reconstitution of the posture of free ranging animal in Bio-logging

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Abstract - In this chapter, we focused on the posture estimation problem of a body moving in 3D space. This study is devoted to the reconstruction of the body attitude and Dynamic Body Acceleration (DBA) in free ranging animal (application in Bio-logging) where the access to GPS locations is limited or impossible. A quaternion-based complementary filter is designed to provide a viable attitude estimation method. We claim that this approach is an alternative to overcome the limitations of the Extended Kalman Filter (EKF). The complementary filter processes data from small inertial/magnetic sensor modules that contains triaxial gyroscopes, accelerometers, and magnetometers without resorting to GPS data. The proposed algorithm incorporates a motion kinematic model and adopts a two-layer filter architecture. In the latter, the Levenberg Marquardt Algorithm (LMA) pre-processes acceleration and local magnetic field measurements to produce what will be called the modelling error. This error together with the angular rate measurements becomes measurement signals for the complementary filter. By this way, the overall approach design is greatly simplified. The efficiency of the approach is experimentally investigated through a free motion of animal. The complementary filter performance is shown also quantitatively using the Root Mean Square Difference (RMSD). The estimated attitude is used after to calculate the DBA for future evaluation of the energetic index of animal and its 3D position.

Key words - Attitude and posture estimation, quaternion, MEMS inertial and magnetic sensors, multi-sensors data fusion, complementary filter, Bio-logging.

1. Introduction

The rigid body attitude and orientation estimation problems are highly motivated from various applications. For example, in rehabilitation and biomedical engineering (Zhou et al. 2006), the attitude is used in stroke rehabilitation exercises to record patient's movements in order to provide adequate feedback for the therapist. In human motion tracking and biomechanics (O'Donovan et al. 2007), the attitude serves as a tool for physicians to perform long-term monitoring of the patients and to study human movements during everyday activities. Moreover, the attitude estimation is extensively used in tracking of handheld microsurgical instrument (Ang et al. 2004). In aerial and marine vehicles (Mahony et al. 2008), the attitude is used to achieve a stable controller.

Recently, the problem of attitude and orientation tracking has been treated in Bio-logging. The latter stands in the intersection of animal behavior and bioengineering and aims at obtaining new information from the natural world and providing new insights into the hidden lives of animal's species (Rutz and Hays 2009; Ropert-Coudert et al. 2009). Bio-logging generally involves a free-ranging animal-attached electronic device (called also bio-logger) that records aspects of the animal's biology (behavior, movement, physiology) (Halsey et al. 2007; Bost et al. 2007) and its environment. Thirty years ago, several tagging technologies such as satellite tracking (the Argos system) (Le Boeuf et al. 2009) and Time-Depth-Recorders (TDRs) (Kooyman 2004) have been used to provide a basic knowledge on the function of free-ranging organisms. The recent advances in electronic miniaturization, sensors and digital information processing allowed researchers studying animal's biology with a high level of detail and across the full range of ecological scales.

Many marine and terrestrial animals are studied during their daily activities. The posture and orientation tracking of these free-ranging animals represents one of the recent biology aspects studied in Bio-logging. Indeed, some scientific researches started to focus on this topic using low-cost sensors based on Micro Electro-Mechanical System (MEMS) technology as a 3-axis accelerometer and a 3-axis magnetometer. The obvious advantage of this new approach is the gain access to the third dimension space, which is the key to a good understanding of the diving strategies observed in these predators (Elkaim et al. 2006). The main question to answer is how it is possible to extract the gravity components of the body animal (Johnson and Tyack 2003; Watanabe et al. 2005; Wilson et al. 2008)? This information is exploited after to deduce the corresponding attitude and consequently the DBA.

In this chapter, we propose the addition of 3-axis gyroscope measurements to the sensors already used (a 3-axis accelerometer and a 3-axis magnetometer) in Bio-logging. The use of gyroscope with accelerometer and magnetometer, mounted in triad configuration, in Bio-logging has not been considered yet in the author’s knowledge. In our opinion, it can improve the estimation precision of the attitude especially during dynamic situation of the animal motion (Mahony et al. 2008; Fourati et al. 2009; Fourati et al. 2011(a)). The main idea of the algorithm is to use a complementary filter coupled with a Levenberg Marquardt Algorithm (LMA) to process the measurements from a 3-axis gyroscope, a 3-axis magnetometer and a 3-axis accelerometer. The proposed approach combines a strap-down system, based on the time integral of the angular velocity, with the LMA that uses the Earth’s magnetic field and the gravity vector to compensate the attitude predicted by the gyroscope. It is important to note that the resulting structure is complementary: high bandwidth rate gyro measurements are combined with low bandwidth vector observations (gravity and Earth’s magnetic field) to provide an accurate attitude estimate. Thanks to the knowledge of the estimated attitude, it is now possible to reconstitute the DBA of the animal in order to evaluate its daily diary (Wilson et al. 2008) (sleeping, walking/flying, running, and hunting) and provide important insights into some of the stresses faced by free-ranging animals especially the King Penguin and Badger. Based on the values of DBA, the problem of 3D position estimation in the case of pedestrian locomotion can be addressed in future works in Bio-logging to reconstruct the trajectory of animal.

This chapter is organized as follows: section 2 describes the problem statement and our motivations for motion estimation in Bio-logging. Section 3 details the attitude parameterization and the sensor measurement models used in this work. Section 4 details the structure of the proposed complementary filter for the attitude estimation. Section 5 is devoted to experimental results and comparisons to illustrate the effectiveness of the proposed algorithm. Finally, section 6 summarizes the main conclusions of the chapter.

2. Motivations and problem formulation

Recent technological advances have revolutionized the approach of the animals in their environment, and have enabled researchers in biology and eco-physiology to leave their laboratories to study these adaptations on the animal models living freely in their natural environment. Bio-logging has been introduced as the science that studies the behavior, physiology, ecology and environment properties of free-living animals (bioclimatic, global change, etc…) that are often beyond the border of our visibility or experience. Bio-logging has found its origin in the marine environment (Kooyman 2004) and has diversified into the study of flying and terrestrial species. This scientific area refers often to the study of free-ranging animals in their natural environment through miniaturized electronic devices, called bio-loggers (Naito, 2004), and usually attached to their bodies. These systems measure and record biological parameters or physico-chemical properties related to the individual and/or its environment using various types of sensors (luminosity, pressure, velocity, etc…). The loggers provide time tracking of physical and biological parameters over periods ranging from several hours to several months or sometimes a year and at sampling rates ranging from minutes to several times per second. The King Penguin and Badger are the major biological models studied in Strasbourg University thanks to the Bio-logging technology. Biologists are recently interested to reconstruct the motion of these animals (3D attitude and position) under several acceleration profiles, to be able to study their behaviour during long periods.

In this chapter, one is interested to propose a robust alternative approach to estimate the attitude or orientation of rigid body (Fourati 2010), which represents the animal body, to be applied after in the case of penguin (see Fig. 1). To achieve this goal, we use a wearable inertial and magnetic MEMS sensors assembly based on an IMU composed of a 3-axis accelerometer, a 3-axis magnetometer and a 3-axis gyroscope. Furthermore, the estimated attitude is used to calculate three components of DBA of the animal, which provides for biologists important information about the energy budgets of free-living animals. This work will serve in future to address the problem of 3D position estimation in the case of animal pedestrian locomotion, based on attitude and DBA estimations.

3. Materials and methods

3.1. Rigid body attitude and coordinate systems

A rigid body is considered as a solid formed from a finite set of material points with deformable volume (Goldstein 1980). Generally, the rigid body attitude represents the direction of its principal axes relative to a reference coordinate system and its dynamics expresses the change of object orientation. In the navigation field, the attitude estimation problem requires the transformation of measured and computed quantities between various frames. The rigid body attitude is based on measurements gained from sensors attached to this latter. Indeed, inertial sensors (accelerometer, gyroscope, etc…) are attached to the body-platform and provide inertial measurements expressed relative to the instrument axes. In most systems, the instrument axes are nominally aligned with the body-platform axes. Since the measurements are performed in the body frame, we describe in Fig. 2 the orientation of the body-fixed frame $B\left(X_B, Y_B, Z_B\right)$ with respect to the Earth-fixed frame $N\left(X_N, Y_N, Z_N\right)$, which is tangent to the Earth's surface (Local Tangent Plane, LTP). This local coordinate is particularly useful to express the attitude of a moving rigid body on the surface of the Earth (Grewal 2001). The X_N-axis points true north. The Z_N-axis points towards the interior of the Earth, perpendicular to the reference ellipsoid. The Y_N-axis completes the right-handed coordinate system, pointing East (NED: North, East, Down).

3.2. Mathematical model of attitude representation

In this chapter, the quaternion algebra is used to describe the rigid body attitude. The unit quaternion, denoted by q, is expressed as:

$$q = q_0 + q_{vect} = q_0 1 + q_1 i + q_2 j + q_3 k \in H \tag{1}$$

where $q_{vect} = q_1 i + q_2 j + q_3 k$ represents the imaginary vector, q_0 is the scalar element and H can be written such as:

$$H = \left\{ q / q^T q = 1,\ q = \begin{bmatrix} q_0 & q_{vect}^T \end{bmatrix}^T,\ q_0 \in \Re,\ q_{vect} = \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix}^T \in \Re^{3\times 1} \right\} \tag{2}$$

The rotation matrix in term of quaternion can be written as:

$$M_N^B(q) = \begin{bmatrix} 2\left(q_0^2 + q_1^2\right) - 1 & 2\left(q_1 q_2 + q_0 q_3\right) & 2\left(q_1 q_3 - q_0 q_2\right) \\ 2\left(q_1 q_2 - q_0 q_3\right) & 2\left(q_0^2 + q_2^2\right) - 1 & 2\left(q_0 q_1 + q_2 q_3\right) \\ 2\left(q_0 q_2 + q_1 q_3\right) & 2\left(q_2 q_3 - q_0 q_1\right) & 2\left(q_0^2 + q_3^2\right) - 1 \end{bmatrix} \tag{3}$$

We invite the reader to refer to (Kuipers 1999) for a more details about quaternion algebra.

3.3. 3-axis inertial/magnetic sensors package measurement models

The sensors configuration consists of a 3-axis accelerometer, a 3-axis magnetometer and a 3-axis gyroscope containing MEMS technologies. A detailed study of these sensors is given in (Beeby 2004).

3.3.1. 3-axis accelerometer

An accelerometer measures the acceleration of the object that it supports. If three accelerometers are mounted in orthogonal triad in a rigid body, such that their sensitive axes coincide with the principal axes of inertia of the moving body. The output of a 3-axis accelerometer in the body-fixed frame (B) is given by the following measurement vector (Guerrero-Castellanos 2008):

$$f = M_N^B(q)(a+G)+\delta_f \tag{4}$$

where $G=\begin{bmatrix}0 & 0 & g\end{bmatrix}^T$ and $a=\begin{bmatrix}a_x & a_y & a_z\end{bmatrix}^T$ represent, respectively, the gravity vector and the DBA of the rigid body, given in the Earth-fixed frame (N). $\delta_f \in \Re^3$ is a noise vector assumed to be independent, white and Gaussian. $M_N^B(q)$ is the rotation matrix defined in (3) and reflecting the transition between the frames (N) and (B).

3.3.2. 3-axis magnetometer

A magnetometer is a device for measuring the direction and intensity of a magnetic field and especially the Earth's magnetic field. The output of a 3-axis magnetometer in the body-fixed frame (B) is given by the following measurement vector (Guerrero-Castellanos 2008):

$$h = M_N^B(q)m+\delta_h \tag{5}$$

where m is the magnetic field expressed in the Earth-fixed frame (N) by:

$$m = \begin{bmatrix} m_x & 0 & m_z \end{bmatrix}^T = \begin{bmatrix} \|m\|\cos(I) & 0 & \|m\|\sin(I) \end{bmatrix}^T \tag{6}$$

δ_h is a white Gaussian noise and $M_N^B(q)$ is expressed in (3). The parameters of the theoretical model of the geomagnetic field m closest to reality can be deduced from (Astrosurf 2012).

3.3.3. 3-axis gyroscope

A gyroscope is an inertial sensor that measures the angular velocity of reference attached to the sensor compared to an absolute reference frame along one or more axes (Titterton and Weston 2004). The output of a 3-axis gyroscope in the body-fixed frame (B) is given by the measurement vector (Guerrero-Castellanos 2008):

$$\omega_G = \omega + b + \delta_G \tag{7}$$

where $\omega \in \Re^3$ is the real angular velocity, $b \in \Re^3$ is a slowly time varying function (Beeby et al. 2004) called also bias and δ_G is a white Gaussian noise.

4. Complementary filter for attitude estimation

In this chapter, the objective is to design an attitude estimation algorithm based on inertial and magnetic MEMS sensors. The application in mind is related to a free-ranging animal case in Bio-logging (Fourati et al. 2011(b)). By considering the rigid body kinematic model, a complementary filter is proposed in order to take advantage from the good short-term precision given by rate gyros integration and the reliable long-term accuracy provided by accelerometer and magnetometer measurements. This leads to better attitude estimates (Mahony et al. 2008). It is important to note that the resulting approach structure is complementary: high bandwidth rate gyro measurements are combined with low bandwidth vector observations to provide an accurate attitude estimate (Brown and Hwang 1997).

4.1. Rigid body kinematic motion equation

The rigid body motion can be described by the attitude kinematic differential equation (Shuster 1993), which represents the time rate of attitude variation, expressed in a quaternion term q, as a result of the rigid body angular rates measured by the gyroscope:

$$\dot{q} = \frac{1}{2}\begin{bmatrix} -q_{vect}^{T} \\ I_{3\times3}q_0 + \left[q_{vect}^{\times}\right] \end{bmatrix}\omega_G \tag{8}$$

where

- $q = \begin{bmatrix} q_0 & q_{vect}^{T} \end{bmatrix}^{T}$ is the unit quaternion that denotes the mathematical representation of the rigid body attitude between two frames: body-fixed frame (B) and Earth-fixed frame (N). Note that $q_{vect} = \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix}^{T}$ represents the vector part of q. It is customary to use quaternion instead of Euler angles since they provide a global parameterization of the body orientation, and are well-suited for calculations and computer simulations.
- ω_G represents the angular velocity vector expressed in (B) and $I_{3\times3}$ is the identity matrix of dimension 3.
- $\left[q_{vect}^{\times}\right]$ represents the standard vector cross-product (the skew-symmetric matrix) which is defined such as:

$$\left[q_{vect}^{\times}\right] = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}^{\times} = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} \tag{9}$$

4.2. The design of state model

Let us consider the following system model (S_1) composed of (8) with the output y that represents the linear measurement model. The output $y \in \Re^6$ of this system is built by stacking the accelerometer and magnetometer measurements.

$$(S_1):\begin{cases}\begin{bmatrix}\dot{q}_0\\ \dot{q}_1\\ \dot{q}_2\\ \dot{q}_3\end{bmatrix}=\frac{1}{2}\begin{bmatrix}-q_{vect}^T\\ I_{3\times3}q_0+\left[q_{vect}^{\times}\right]\end{bmatrix}\omega_G=\frac{1}{2}\begin{bmatrix}-q_1\omega_{Gx}-q_2\omega_{Gy}-q_3\omega_{Gz}\\ q_0\omega_{Gx}-q_3\omega_{Gy}+q_2\omega_{Gz}\\ q_3\omega_{Gx}+q_0\omega_{Gy}-q_1\omega_{Gz}\\ q_1\omega_{Gy}-q_2\omega_{Gx}+q_0\omega_{Gz}\end{bmatrix}\\ y=\begin{bmatrix}f_x & f_y & f_z & h_x & h_y & h_z\end{bmatrix}^T\end{cases} \tag{10}$$

By considering the rigid body kinematic equation and the linear measurement model y, the proposed system (S_1) can take advantage from the good short term precision given by the rate gyros integration and the reliable long term accuracy provided by accelerometers and magnetometers measurements fusion (Brown and Hwang 1997; Fourati et al. 2010), which leads to improve the quaternion estimation.

4.3. Attitude complementary filter design

The aim of this approach is to ensure a compromise between the accuracy provided by short-term integration of the gyroscope data and the long-term measurements precision obtained by the accelerometer and the magnetometer. To compensate for the drifts on the estimated quaternion that are observed during the integration of the differential equation (8), a correction term T is introduced in this equation based on a quaternion product $\otimes$. We propose the following complementary filter:

$$(F):\begin{bmatrix}\dot{\hat{q}}_0\\ \dot{\hat{q}}_1\\ \dot{\hat{q}}_2\\ \dot{\hat{q}}_3\end{bmatrix}=\frac{1}{2}\begin{bmatrix}-\hat{q}_1\omega_x-\hat{q}_2\omega_y-\hat{q}_3\omega_z\\ \hat{q}_0\omega_x-\hat{q}_3\omega_y+\hat{q}_2\omega_z\\ \hat{q}_3\omega_x+\hat{q}_0\omega_y-\hat{q}_1\omega_z\\ \hat{q}_1\omega_y-\hat{q}_2\omega_x+\hat{q}_0\omega_z\end{bmatrix}\otimes T \tag{11}$$

where $\hat{q}=\begin{bmatrix}\hat{q}_0 & \hat{q}_1 & \hat{q}_2 & \hat{q}_3\end{bmatrix}^T\in\Re^4$ represents the estimated quaternion. The correction term T is calculated from a fusion approach of accelerometer and magnetometer data. The quaternion product introduced in (11) allows to merge the magnetic and inertial measurements. Let us present the method for calculating the correction term T . We consider the modeling error $\delta(\hat{q}) = (y - \hat{y})$. The estimated output is given by $\hat{y}$:

$$\hat{y} = \begin{bmatrix} \hat{f}_x & \hat{f}_y & \hat{f}_z & \hat{h}_x & \hat{h}_y & \hat{h}_z \end{bmatrix}^T \tag{12}$$

Measurements of the estimated accelerations $\hat{f}_x$, $\hat{f}_y$ and $\hat{f}_z$ can be calculated by assuming that the DBA a is low $\left(\|a\|_2 \ll \|G\|_2\right)$ (Fourati et al. 2010). Thus we obtain:

$$\hat{f} = \begin{bmatrix} 0 & \hat{f}_x & \hat{f}_y & \hat{f}_z \end{bmatrix}^T = \hat{q}^{-1} \otimes G_q \otimes \hat{q} \tag{13}$$

where

$G_q = [0 \quad 0 \quad 0 \quad 9.8]^T$: Quaternion representation of the gravity vector $G = [0 \quad 0 \quad 9.81]^T$.

Measurements of the estimated Earth’s magnetic field $\hat{h}_x$, $\hat{h}_y$ and $\hat{h}_z$ can be calculated such as:

$$\hat{h} = \begin{bmatrix} 0 & \hat{h}_x & \hat{h}_y & \hat{h}_z \end{bmatrix}^T = \hat{q}^{-1} \otimes m_q \otimes \hat{q} \tag{14}$$

where

$m_q = [0 \quad m_x \quad 0 \quad m_z]^T$: Quaternion representation of the Earth’s magnetic field $m = [m_x \quad 0 \quad m_z]^T$.

The minimization of the modeling error $\delta(\hat{q})$ is performed from a regression method that minimizes the scalar squared error criterion function $\xi(\hat{q})$ related to $\delta(\hat{q})$:

$$\xi(\hat{q}) = \delta(\hat{q})^T \delta(\hat{q}) \tag{15}$$

In this chapter, the LMA (Marquardt 1963) is used to minimize the non-linear function $\xi(\hat{q})$. This choice reflects the robustness demonstrated by this algorithm compared to other methods such as Gauss-Newton or gradient (Dennis et al. 1983).

The unique solution to this problem can be written in the following form (Deutschmann et al. 1992):

$$\eta(\hat{q}) = K\delta(\hat{q}) \tag{16}$$

where $K = k\left[X^T X + \lambda I_{3\times3}\right]^{-1} X^T$ is the gain of the filter used to minimize the error $\delta(\hat{q})$. $X \in \Re^{6\times3}$ is the Jacobian matrix defined by:

$$X = -2\left[\left[f^{\times}\right] \quad \left[h^{\times}\right]\right]^T = -2\begin{bmatrix} 0 & -f_z & f_y & 0 & -h_z & h_y \\ f_z & 0 & -f_x & h_z & 0 & -h_x \\ -f_y & f_x & 0 & -h_y & h_x & 0 \end{bmatrix}^T \tag{17}$$

The constant λ is chosen to ensure the non-singularity of the minimization problem. The constant k determines the crossover frequency of the latter. It is used to tune the balance between measurement noises suppression and response time of the filter. Generally, it combines low bandwidth accelerometer/magnetometer readings with high bandwidth gyroscope measurements. Notice that, the complementary filter has a better convergence when k is chosen somewhere between 0.1 and 1 (Mahony et al. 2008). $\eta(\hat{q})$ represents a part of the correction term T. To achieve the quaternion product in (11), the term T must be of dimension 4. So, T is constructed as follows:

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & & & & & & \\ 0 & & & K & & & \\ 0 & & & & & & \end{bmatrix} \begin{bmatrix} 1 \\ \delta(\hat{q}) \end{bmatrix} \tag{18}$$

The scalar part of quaternion error is chosen to 1 to force the error quaternion to represent small angles of rotation (Deutschmann et al. 1992). Finally, the complementary filter can be written as follows:

$$(F):\begin{bmatrix}\dot{\hat{q}}_0\\ \dot{\hat{q}}_1\\ \dot{\hat{q}}_2\\ \dot{\hat{q}}_3\end{bmatrix}=\frac{1}{2}\begin{bmatrix}-\left(\hat{q}_1\omega_x+\hat{q}_2\omega_y+\hat{q}_3\omega_z\right)\\ \left(\hat{q}_0\omega_x-\hat{q}_3\omega_y+\hat{q}_2\omega_z\right)\\ \left(\hat{q}_3\omega_x+\hat{q}_0\omega_y-\hat{q}_1\omega_z\right)\\ \left(\hat{q}_1\omega_y-\hat{q}_2\omega_x+\hat{q}_0\omega_z\right)\end{bmatrix}\otimes\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & & & & & & \\ 0 & & & K & & & \\ 0 & & & & & & \end{bmatrix}\begin{bmatrix}1\\ \delta(\hat{q})\end{bmatrix} \qquad (19)$$

5. Experimental validation

5.1. Experimental tool for attitude estimation: Inertial Measurement Unit MTi-G

In order to evaluate the efficiency of the proposed complementary filter in real world applications, an experimental setup was developed resorting to an inertial and magnetic sensor assembly. The goal is to obtain an estimation of the quaternion that represents the orientation of a rigid body and to investigate its accuracy under various conditions. For the experiments, the *MTi-G* from Xsens Motion Technologies (Xsens Technologies 2012) was employed. This MEMS device is a miniature, lightweight, 3D calibrated digital output sensor (3D acceleration from accelerometer, 3D angular rate from gyroscope, and 3D magnetic field data from magnetometer), a GPS enhanced Attitude and Heading Reference System with built-in bias, sensitivity, and temperature compensation. The *MTi-G* outputs data at a rate of 100 Hz and records them on a computer (see Fig. 3). In addition, this device is designed to track the body 3D attitude output in quaternion representation using an embedded Extended Kalman filter algorithm. The calibration procedure to obtain the gain, offsets and non-orthogonality of the sensors was performed by the manufacturer of the sensor module.

It is important to note that the *MTi-G* device serves as tool for the evaluation of the complementary filter efficiency and cannot be suitable for use in Bio-logging field due to its dependence on an energy source as well as its heavy weight. In the following set of experiment, the calibrated data from the *MTi-G* are used as input to the complementary filter.

5.2. Evaluation test and estimation attitude analysis in free movement of animal

In this set of experiments, the accuracy of the complementary filter is evaluated during the free motion of a domestic animal (a dog). The *MTi-G* is attached to the back of the animal with its *xyz* axes aligned with those of the dog. The path followed by the animal was carried out in a football stadium as shown in Fig. 4. Inertial/magnetic measurements and attitude (in quaternion representation) are recorded using the *MTi-G* during the motion of the dog (see Fig. 5) and transmitted to a computer via USB port. It should be noted that, based upon measurements recorded by the accelerometer, we note that the animal motion consists of two acceleration profiles, one corresponding to the low frequencies of motion (during walk) and the other rather to the high frequencies (during trot and canter). The acceleration profile varies between [-15, 15 m/s^2] for f_x and f_y and [-5, +25 m/s^2] for f_z. The increase in the acceleration level between the natural gaits is due to the DBA a of the dog that is more important during the trot and the canter. The recorded inertial and magnetic measurements from the *MTi-G* are used to estimate the attitude using the proposed complementary filter. The calculated attitude from the *MTi-G* is considered as reference of the dog's motion. Fig. 6 plots the evolution of the difference between the calculated quaternion using the *MTi-G* and the one estimated by the proposed approach. Although some parts of the motion are with high dynamics, we can remark that the errors on quaternion's components don't exceed 0.03 on q_0, q_1, q_2 and 0.05 on q_3. For more clarity to the reader, we also represent the attitude estimation results of the same movement using the Euler angles (roll, pitch and yaw). Fig. 7 shows the evolution of the difference between the Euler angles estimated by the complementary filter and the *MTI-G*.

It is clear that this mismatch between the estimated attitude by our approach and the *MTi-G* is small. Then, one can conclude about the performance of the complementary filter in attitude estimation of the animal body even in dynamic situations. Although our approach didn't exploit a GPS data as done in *MTi-G*, it is able to reconstruct the orientation of the dog given by the *MTi-G* with a small error.

5.2. Performance's comparison with previous Bio-logging works

We propose in this section a comparative study between the performance of the attitude estimation obtained from three methods: the complementary filter and two other approaches that have been proposed in Bio-logging that we called method_1 (Wilson et al. 2008) and method_2 (Watanabe et al. 2005). Both approaches use only a combination of triaxial accelerometer and magnetometer and provide an attitude estimation in Euler angles representation. The purpose of this comparison is to analysis the performance of the complementary filter and to prove if it is possible to make an improvement of the attitude estimation in Bio-logging and show the interest to add gyroscope in such application. This comparison is performed in the case of experimental test on the dog, presented earlier and we used the measurements recorded by the *MTi-G*. To compare the three methods, the estimated quaternion from the complementary filter is converted to Euler angles using the formulas presented in (Phillips et al. 2001). The estimation results obtained separately from the three approaches (method_1, method_2 and the complementary filter) are compared with those provided by the internal algorithm of the *MTi-G*.

5.2.1. Attitude estimation

The results of this comparison, illustrated in Fig. 8, show the errors obtained from the difference between the estimates of Euler angles calculated by the *MTi-G* and those provided by the three methods. The smallest difference was obtained with the complementary filter. This error does not exceed 5 ° on the three Euler angles even in high-frequency movements of the animal, where the DBA is important. The estimation errors obtained by method_1 and method_2 are around 10°

for roll and pitch angles and 20° for the yaw angle. These large errors are mainly due to the approximations established in these two methods, since the accelerometer does not extract the attitude during the dynamic situations of movement. These high frequency dynamics are present during the motion of the dog.

Performance's analysis of each method can also be established using the Root Mean Square Difference (*RMSD*). This criterion quantifies the difference between the Euler angles calculated by the *MTi-G*, considered as reference, and those estimated by each method. The *RMSD* was calculated such as:

$$RMSD_{sliding}(k) = \sqrt{\frac{\sum_{i=k}^{n+k}\left(x_i - \hat{x}_i\right)^2}{N}} \tag{20}$$

where

x_i : The Euler angle measured by the *MTi-G* algorithm

$\hat{x}_i$: The Euler angle estimated by the chosen method (complementary filter, method_1 or method_2)

N : The time interval ($T = 2$)

An average of $RMSD_{sliding}$ on the Euler angles for each method is subsequently established in Table 1. Note that the $RMSD_{sliding}$ values relating to the three Euler angles are obtained also with the complementary filter. This highlights the improvements we were able to make at the attitude estimation comparing to the two methods developed in Bio-logging.

5.2.2. Dynamic Body Acceleration estimation

In this subsection, we are interested to the calculation of the DBA of the animal during its movement. This acceleration relates solely to the movement of the animal's body. To calculate the DBA, we used the attitude estimation $\hat{q}$ obtained from the complementary filter during the movement of the dog. The following equation is used:

$$\hat{a} = inv\left(M_N^B\left(\hat{q}\right)\right) f - G \tag{21}$$

where the rotation matrix $M_N^B\left(\hat{q}\right)$ is expressed in (3), $G \in \Re^3$ is the gravity vector and $f \in \Re^3$ represents the measurements of the accelerometer.

We calculate after the norm of the acceleration using the following equation:

$$\left\|\hat{a}\right\|_2 = \sqrt{\hat{a}_x^2 + \hat{a}_y^2 + \hat{a}_z^2} \tag{22}$$

Similarly, we calculated the attitude by method_1 and method_2. The attitude values obtained from each method are used to calculate the DBA of the animal using (21). Finally, the norm of the acceleration is calculated using (22). We report in Fig. 9 the results of this comparison by establishing the difference between the norm of acceleration obtained from the *MTi-G* and the one provided by each method (complementary filter, method_1 and method_2). The smallest difference is obtained with the complementary filter. Indeed, the errors of the complementary filter do not exceed 0.7 m/s^2 but they reach 3 m/s^2 for method_1 and 2 m/s^2 for method_2. These results demonstrate the improvements made by the proposed approach in calculating the DBA of the animal. We recall that a more precise calculation of the DBA will allow biologists a better assessment of energy expenditure of the animal.

Similarly, we used the $RMSD_{sliding}$ given in (20) to measure the difference between the norm of DBA calculated by the *MTi-G* (reference) and the one estimated by each method. We used for that the following notations:

x_i : The norm of DBA calculated by the *MTi-G*.

$\hat{x}_i$: The norm of DBA estimated by the chosen method (complementary filter, method_1 or method_2)

Table 2 shows the averages of the $RMSD_{sliding}$ corresponding to the norm of DBA for each method. Note that we obtained the smallest value of this average with the complementary filter. We conclude that this criterion reflects the filter's ability to provide a more accurate calculation of DBA.

6. Conclusion

This paper presents the design and experimental results of a quaternion-based complementary filter for animal body motion tracking using inertial/magnetic sensor modules containing orthogonally mounted triads of accelerometers, angular rate sensors, and magnetometers. The complementary filter was designed in order to be able to produce highly accurate orientation estimates without resorting to GPS data. The filter design makes use of a simple kinematic motion equation to describe the system model. The filter design is further simplified by preprocessing accelerometer and magnetometer data using the Levenberg Marquardt Algorithm. The modelling error produced by the LMA is provided as input to the filter along with angular rate data. Some experiments are carried out on a free motion of animal through sensor measurements provided by an IMU. From the experiments designed to validate filter performance, this approach was shown to work well. Future works will focus on designing a low-cost, lightweight and embedded prototype for this application.

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Figure captions

Fig.1 Schematic diagram of how an Inertial Measurement Unit is attached to a penguin

Fig. 2 The coordinate system (B) of a rigid body represented in the Earth- fixed frame (N)

Fig. 3 Inertial Measurement Unit *MTi-G*

Fig. 4 The *MTi-G* attached to the back of the dog - Description of the dog motion

Fig. 5 Inertial and magnetic measurements recorded from the *MTi-G*

Fig. 6 Differences between quaternion's estimates provided by the complementary filter and the *MTi-G* during the motion of the dog

Fig. 7 Differences between Euler angles estimates produced by the complementary filter and the *MTi-G* during the motion of the dog

Fig. 8 Estimation errors of Euler angles during the motion of the dog - (a) difference between *MTi-G* and method_1 - (b) difference between *MTi-G* and complementary filter - (c) difference between *MTi-G* and method_2

Fig. 9 Estimation error of the norm of DBA during the motion of the dog

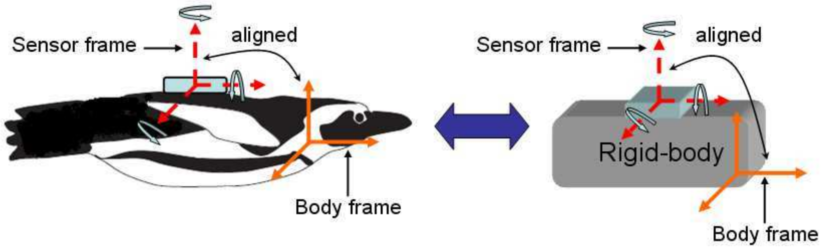


Fig.1. Schematic diagram of how an Inertial Measurement Unit is attached to a penguin

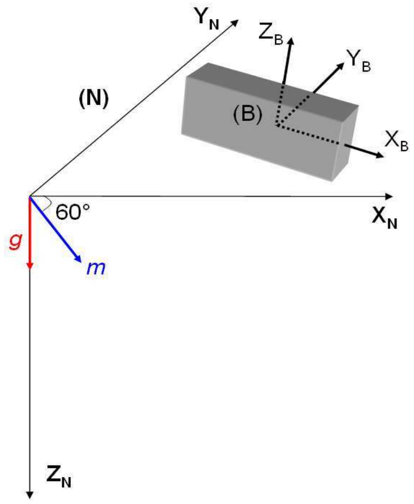


Fig. 2. The coordinate system (B) of a rigid body represented in the Earth- fixed frame (N)

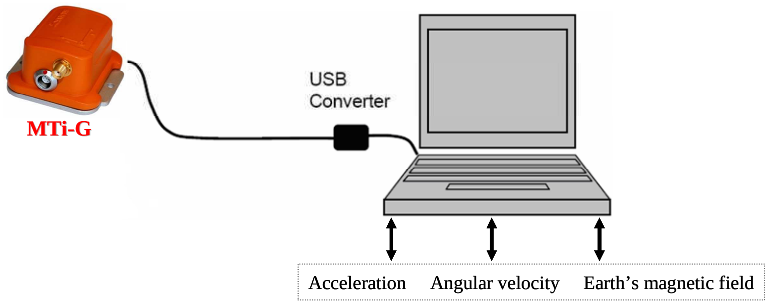


Fig. 3. Inertial Measurement Unit *MTi-G*

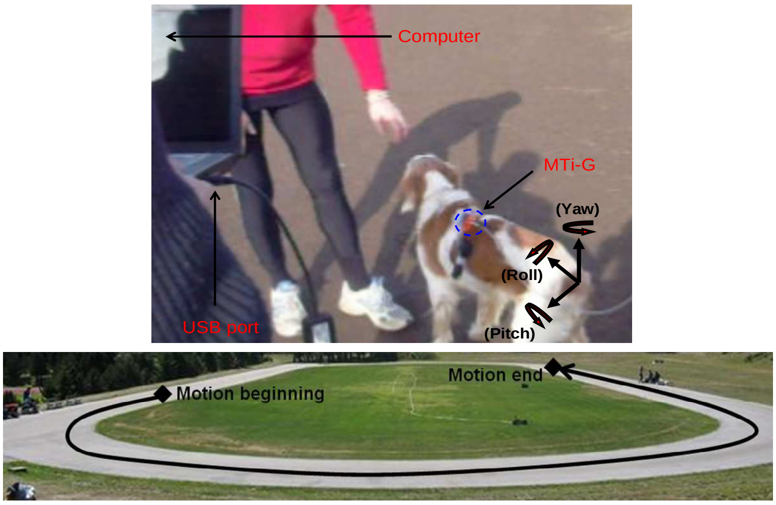


Fig. 4. The *MTi-G* attached to the back of the dog - Description of the dog motion

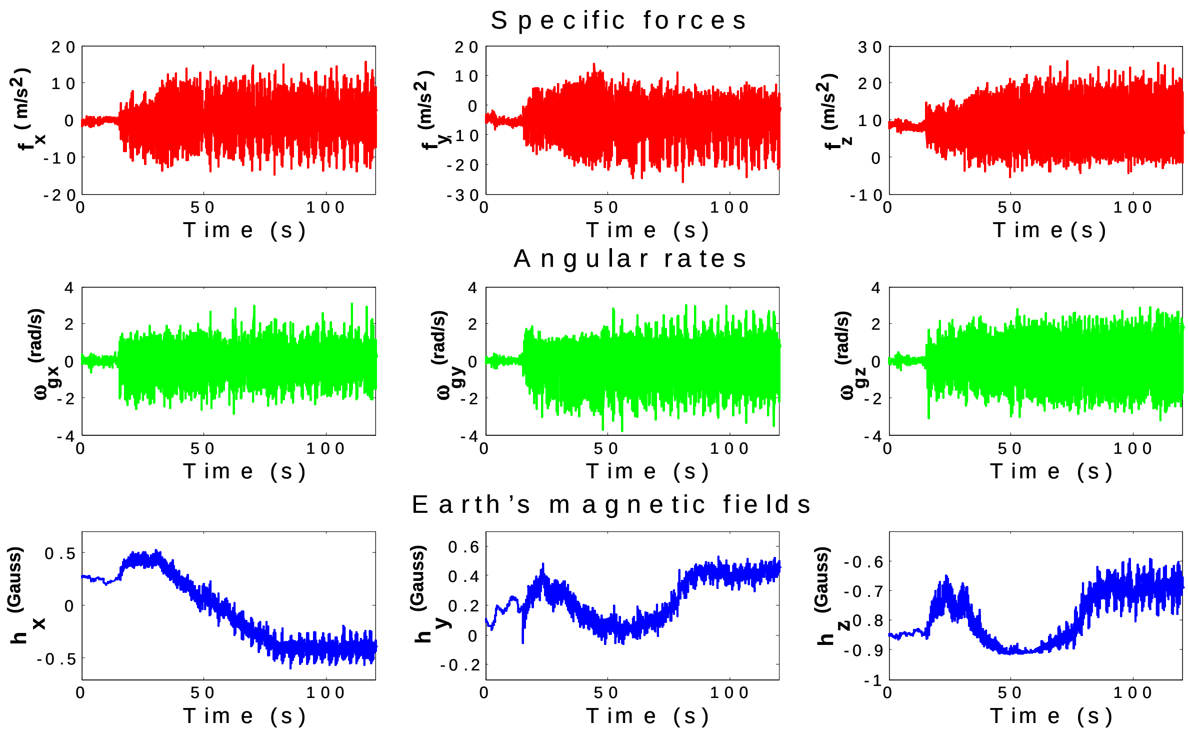


Fig. 5. Inertial and magnetic measurements recorded from the *MTi-G*

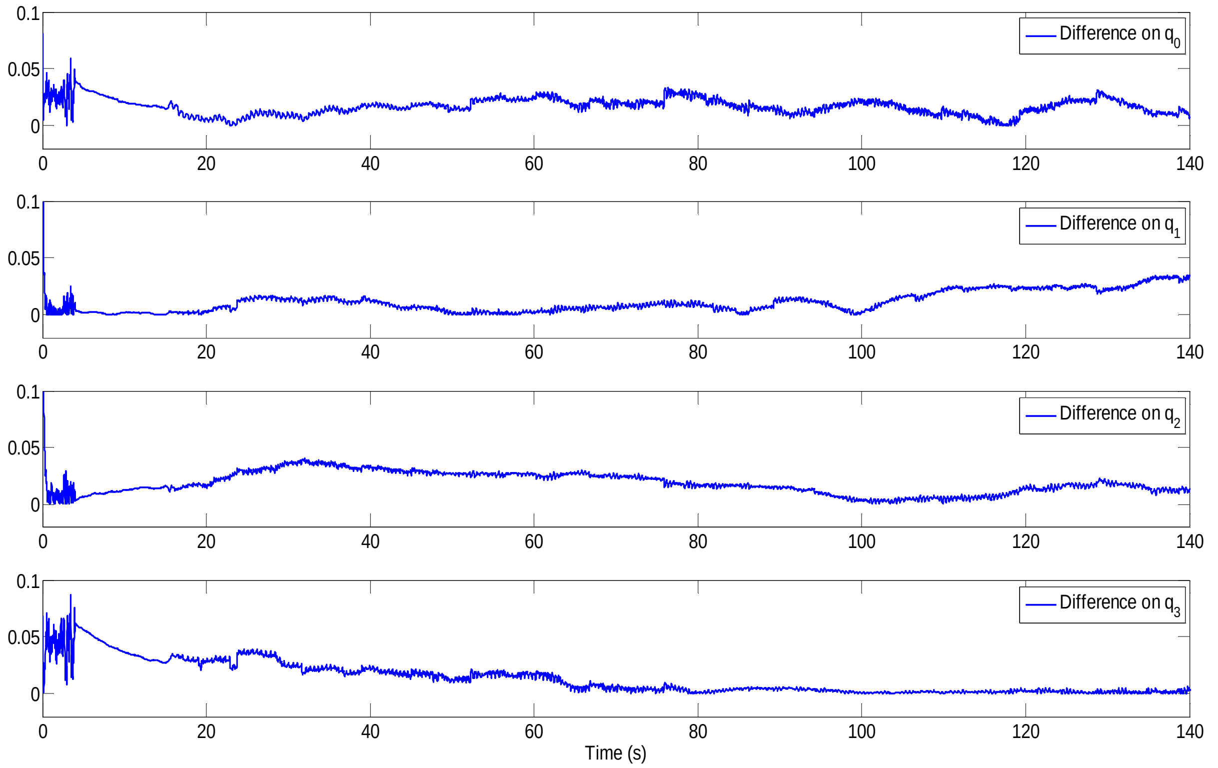


Fig. 6. Differences between quaternion's estimates provided by the complementary filter and the *MTi-G* during the motion of the dog

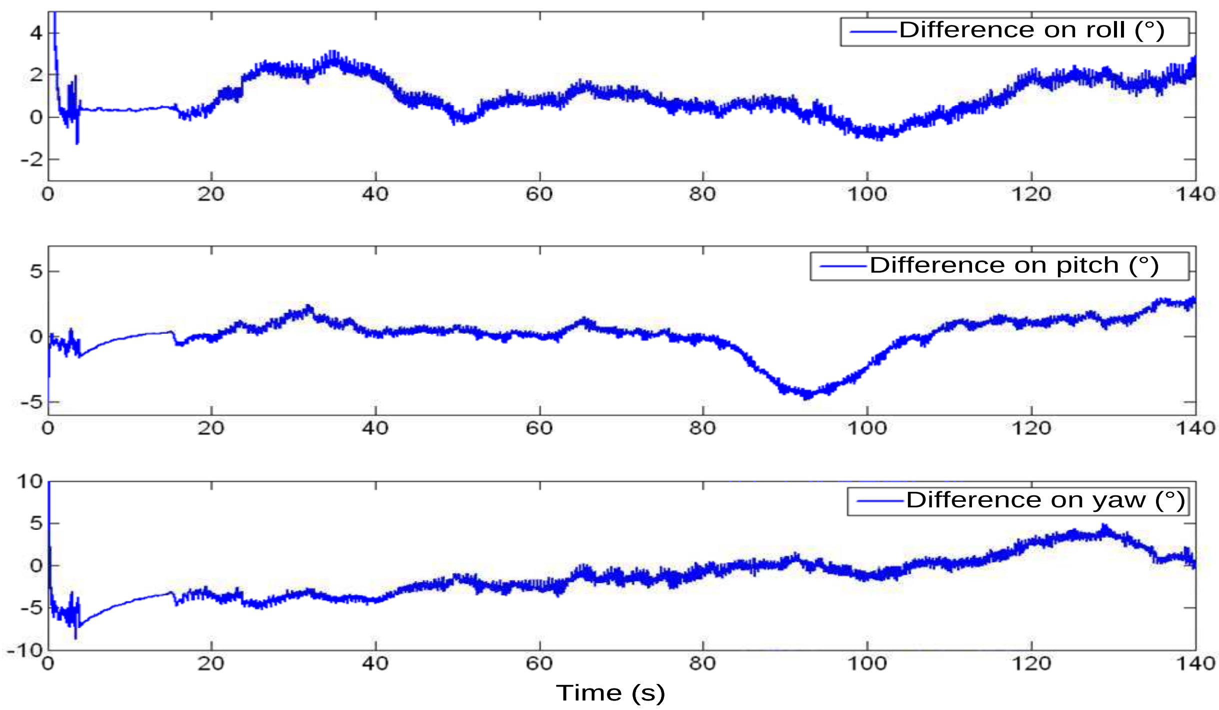
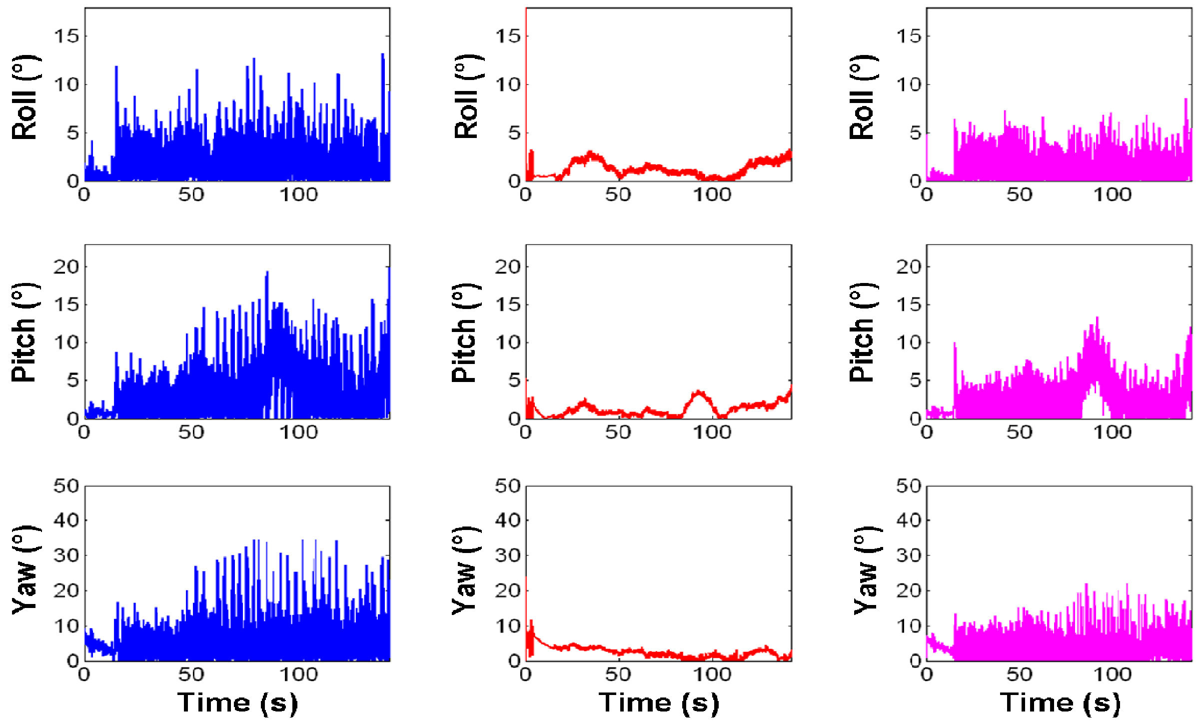


Fig. 7. Differences between Euler angles estimates produced by the complementary filter and the *MTi-G* during the motion of the dog



(a) (b) (c)

Fig. 8. Estimation errors of Euler angles during the motion of the dog - (a) difference between *MTi-G* and method_1 - (b) difference between *MTi-G* and complementary filter - (c) difference between *MTi-G* and method_2

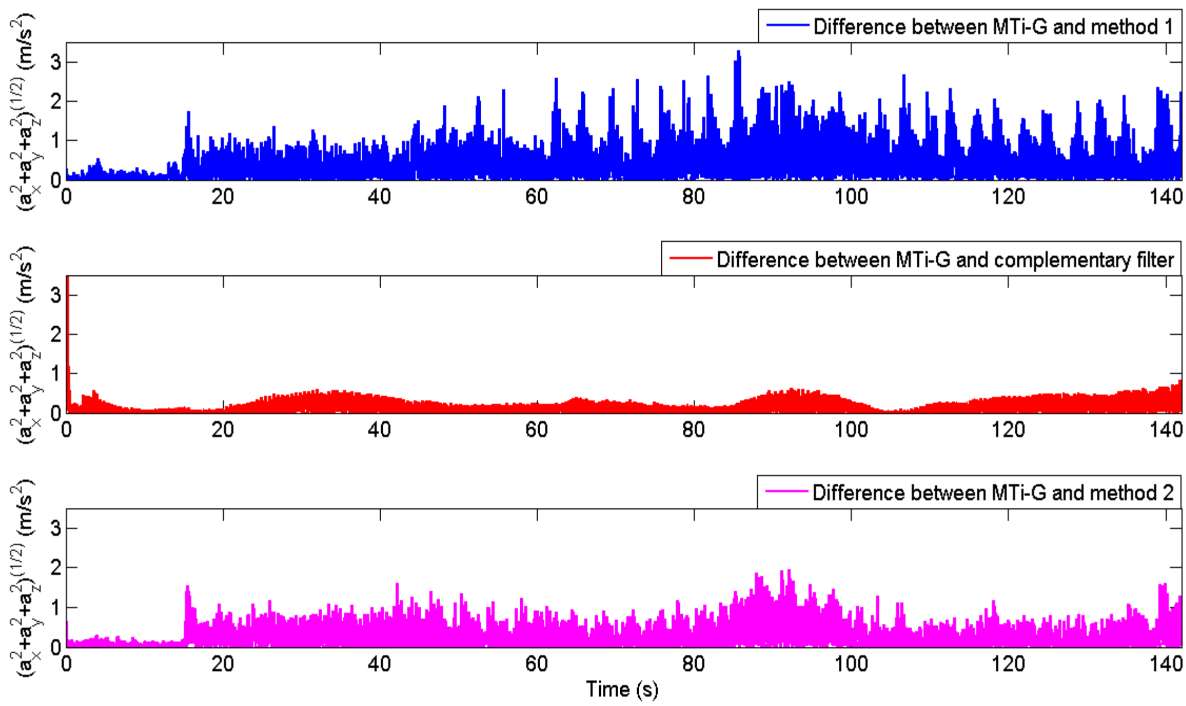


Fig. 9. Estimation error of the norm of DBA during the motion of the dog

Table 1
Average of the $RMSD_{Sliding}$ corresponding to Euler angles for each method during the experiment on the dog

Methods	Complementary filter	Method_1	Method_2
Average of the $RMSD_{Sliding}$ (Roll)	0.934	1.6144	1.1846
Average of the $RMSD_{Sliding}$ (Pitch)	0.8609	2.4962	1.8019
Average of the $RMSD_{Sliding}$ (Yaw)	5.0426	19.1813	12.6655

Table 2
Average of the $RMSD_{Sliding}$ corresponding to the norm of DBA for each method during the experiment on the dog

Methods	Complementary filter	Method_1	Method_2
Average of the $RMSD_{Sliding}$	0.1168	0.3351	0.1929